# Zb(b) as a benchmark for MSSM Hb(b): theory

February 2006

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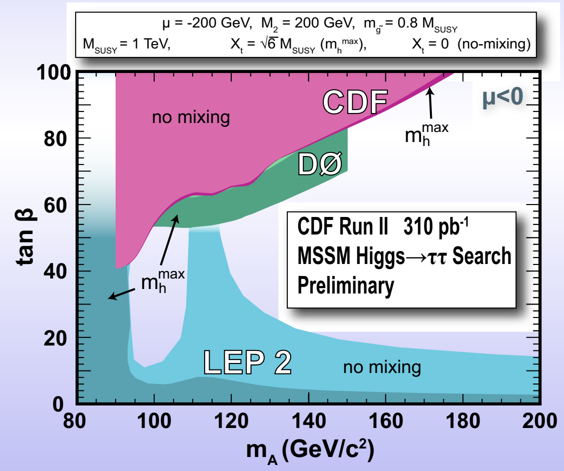
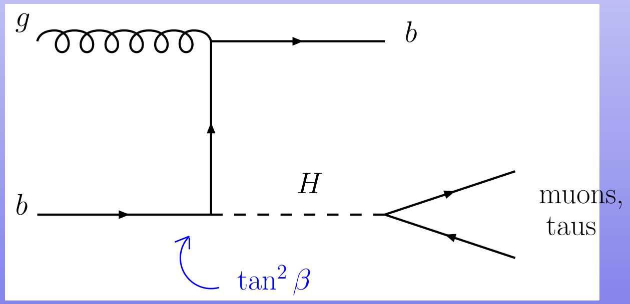
(with thanks to F. Maltoni)

# $H + b$ production

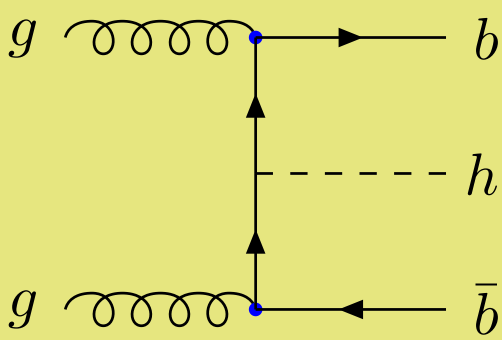
- In some extensions of the Standard Model, there may be more than one Higgs boson.
- For instance, the two-Higgs-doublet model contains three neutral Higgs bosons and the Higgs coupling to bottom quarks may be enhanced by an unknown parameter $\tan\beta$.
- Allowed values of $\tan\beta$ depend on the exact details of the proposed model. However, it has been constrained both at LEP and the Tevatron and its value can be large ($m_A =$ Higgs mass).
- This allows the possibility of discovering such a Higgs at the LHC via its production in association with a high momentum bottom quark.



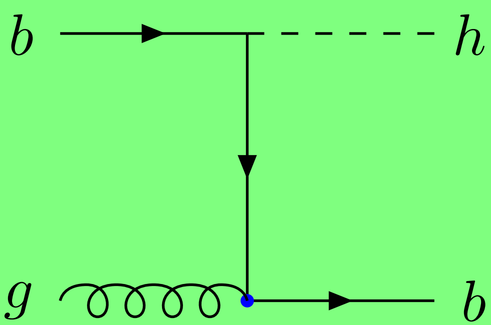



# $H + b$ calculations

- Use the $gg \to Hb\bar{b}$ process and perform the calculation with the $b$-quark massive.
- The collinear divergence in the $g \to b\bar{b}$ splitting is regulated by the mass, so one can compute the rate when only one $b$-quark is observed.
- No $b$-quark PDF $\longrightarrow$ "4-flavour scheme".

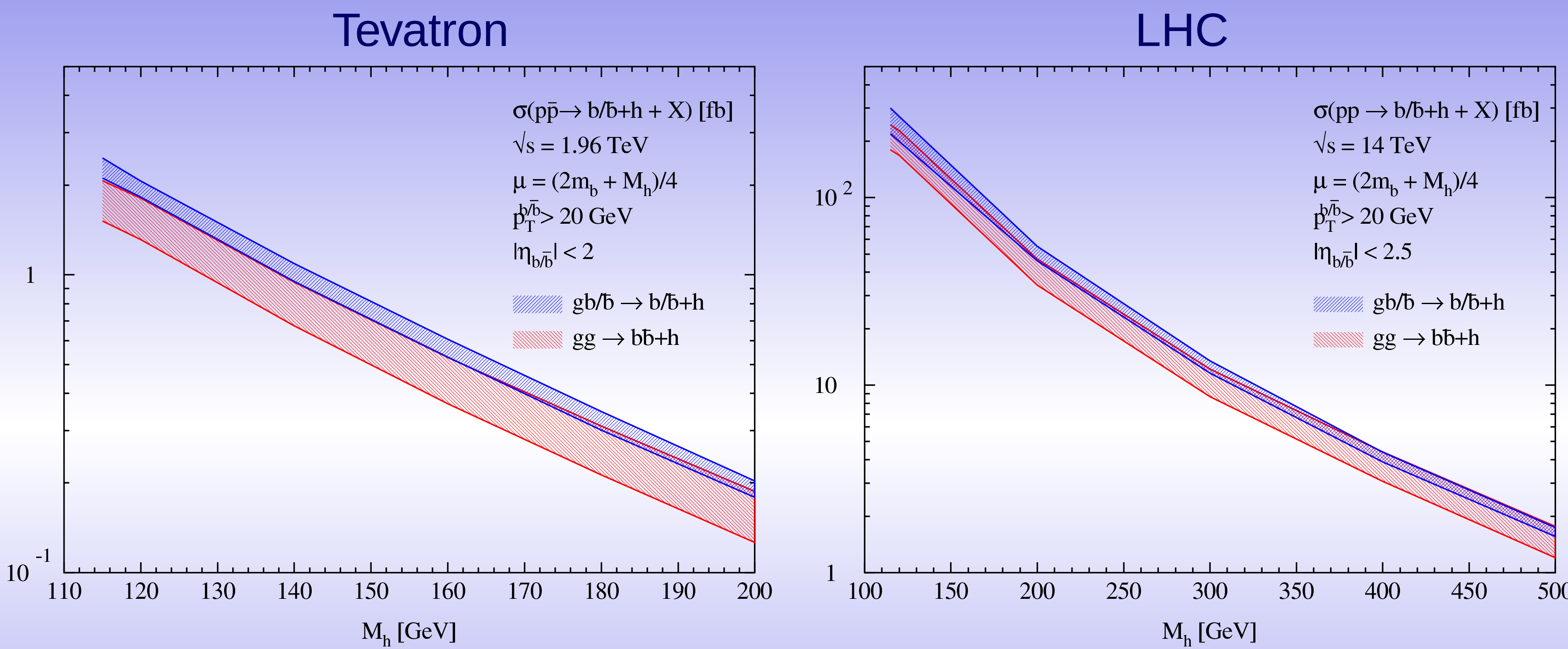



- Absorb the gluon splitting into the $b$-quark PDF, so the basic process is $gb \to Hb$.
- There is no need to retain the $b$-quark mass.
- Large logarithms of the form $\alpha_s \ln(m_H^2/m_b^2)$ are resummed into the $b$-quark PDF, hence "5-flavour scheme".




Approaches should agree; both can be calculated at NLO.

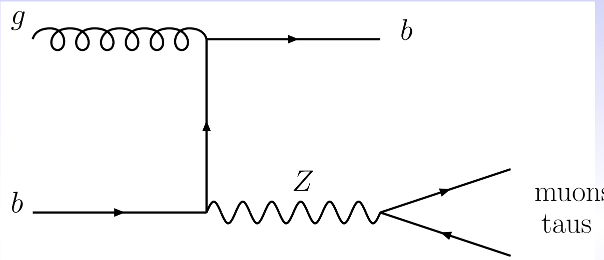
# *Comparison*




- 5-flavour scheme: JC, Ellis, Maltoni, Willenbrock (MCFM).
  4-flavour scheme: Dittmaier, Kramer, Spira;
  Dawson, Jackson, Reina, Wackeroth.
- Taken from 2003 Les Houches report, hep-ph/0405302.
  Uncertainties based on variation of factorization and renormalization scales by a factor of two.

# $Z + b$ *as a test case*

- The production of $Z + b$ is very similar to that of $H + b$, even lying in a similar kinematic region for a low mass Higgs.
- Theoretically, the two processes have the same inputs and uncertainties.
  - same initial state, similar $(x, Q^2)$
  - the same $H$ and $Z$ decays




- Test the experimental analysis procedure by re-discovering the $Z$ –

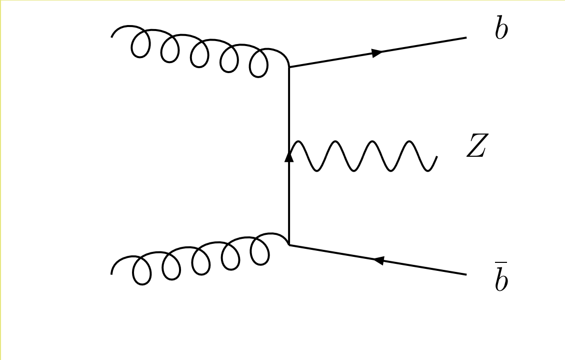
  a) $Z+$ one jet which is b-tagged;

  b) $Z+$ two jets, one or more b-tags.

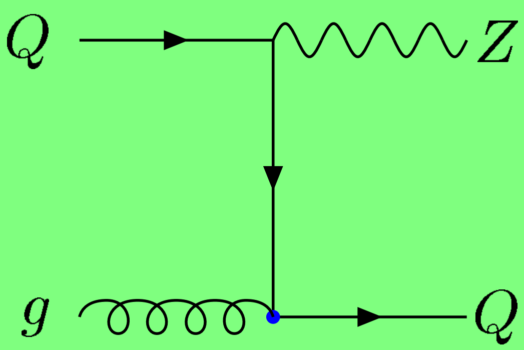
- Furthermore, for low Higgs masses a significant source of background events could come from the production of a slightly off-shell $Z$ boson and a bottom quark at high $p_T$.

# $Z + b$ *calculations*

- Use the $gg \to Zb\bar{b}$ process and perform the calculation with the $b$-quark massive.
- The collinear divergence in the $g \to b\bar{b}$ splitting is regulated by the mass, so one can compute the rate when only one $b$-quark is observed.
- No $b$-quark PDF, "4-flavour scheme" (4FS).




- Absorb the gluon splitting into the $b$-quark PDF, so the basic process is $gb \to Zb$.
- There is no need to retain the $b$-quark mass.
- Large logarithms of the form $\alpha_s \ln(m_Z^2/m_b^2)$ are resummed into the $b$-quark PDF, hence "5-flavour scheme" (5FS).

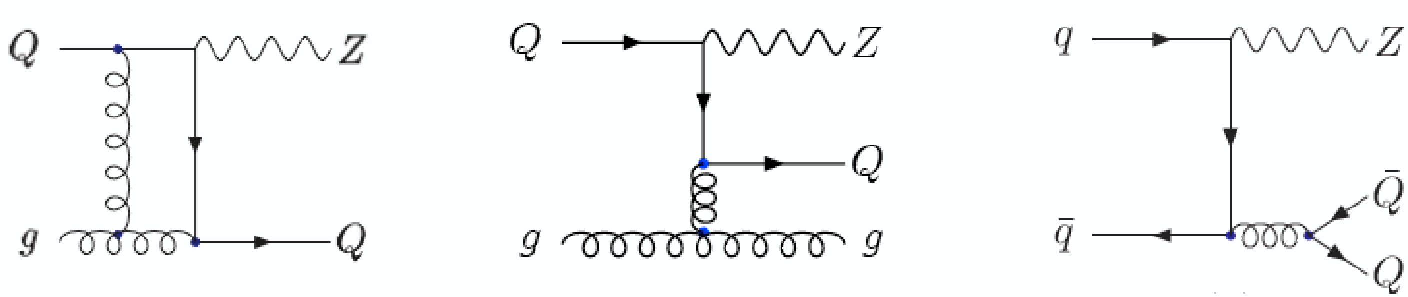



Unlike before, only the 5-flavour scheme can be calculated to NLO.

# $Z + b$ *in the 5FS*

## Leading order:


## Next-to-leading order :




Note: Non $b$-initiated process enters at NLO (present at LO in 4FS).

# *MCFM overview*

(JC and R.K. Ellis + F. Tramontano, F. Maltoni, S. Willenbrock)

| | |
|---|---|
| $p\bar{p} \to W^\pm/Z$ | $p\bar{p} \to W^+ + W^-$ |
| $p\bar{p} \to W^\pm + Z$ | $p\bar{p} \to Z + Z$ |
| $p\bar{p} \to W^\pm + \gamma$ | $p\bar{p} \to W^\pm/Z + H$ |
| $p\bar{p} \to W^\pm + g^\star\,(\to b\bar{b})$ | $p\bar{p} \to Zb\bar{b}$ |
| $p\bar{p} \to W^\pm/Z +$ 1 jet | $p\bar{p} \to W^\pm/Z +$ 2 jets |
| $p\bar{p}(gg) \to H$ | $p\bar{p}(gg) \to H +$ 1 jet |
| $p\bar{p}(VV) \to H +$ 2 jets | $p\bar{p} \to t + q$ |
| $p\bar{p} \to H + b$ | $p\bar{p} \to Z + b$ |
| $p\bar{p} \to W + t$ | |

- Emphasis on a NLO library of signal and background processes.
- Where appropriate, calculations include the decays of the $W$, $Z$ and top quark, including spin correlations.
- Cuts can be applied to all particles, any relevant histograms filled.
- Available at `http://mcfm.fnal.gov`.

# *NLO reminders*

- Almost all experimental analyses rely on either NLO calculations or analytically resummed results (or both).
- Leading order calculations provide information on generic features of events, but do not predict the total number of events accurately.
- This information can first be provided at NLO, where the cross section is under much better control (reduced scale dependence).
- Although any differential distributions can be predicted, such NLO programs involve events with negative weights. As such, predictions are parton-level only – no showering, hadronization or detector simulation.
- Real radiation diagrams contain an additional parton. Either it is:
  - ⋆ clustered with another – so that a jet contains 2 partons;
  - ⋆ or, it provides an additional jet. Unlike the parton shower approach, the kinematics of the extra jet are exact and radiation at large angles is described correctly.

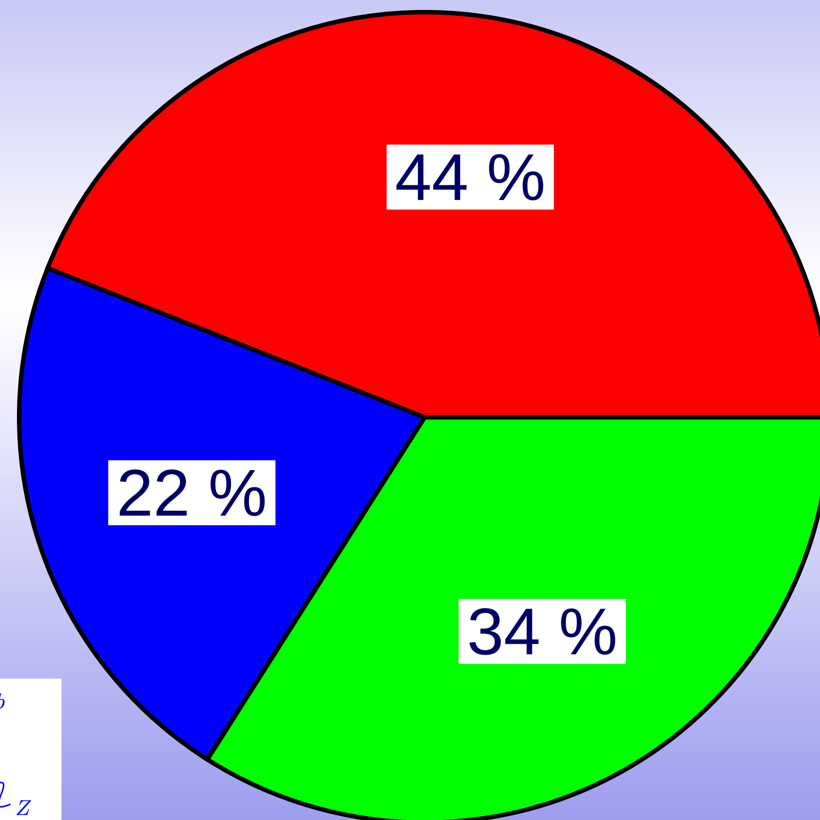
# $Z + b$ at the Tevatron

JC, K. Ellis, F. Maltoni and S. Willenbrock, hep-ph/0312024

- Cuts: $p_T^{\rm jet} > 15$ GeV, $|\eta^{\rm jet}| < 2$.
- $\sigma(Z + \text{ one } b \text{ tag}) = 20$ pb.
- Fakes from $Z+$ jet events are significant.
- Prediction for ratio of $Z + b$ to untagged $Z + \text{jet}$ is

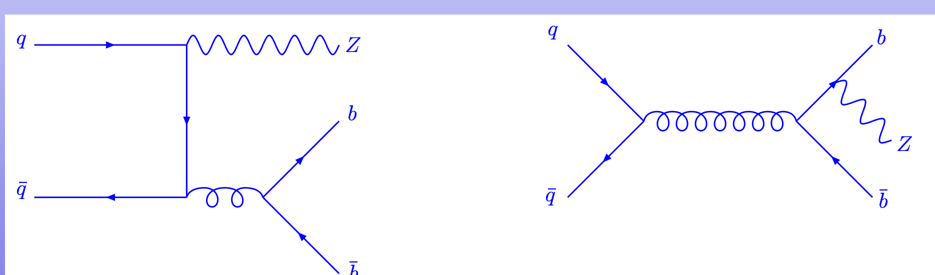
  $0.02 \pm 0.004$ .

$gb \to Zb$



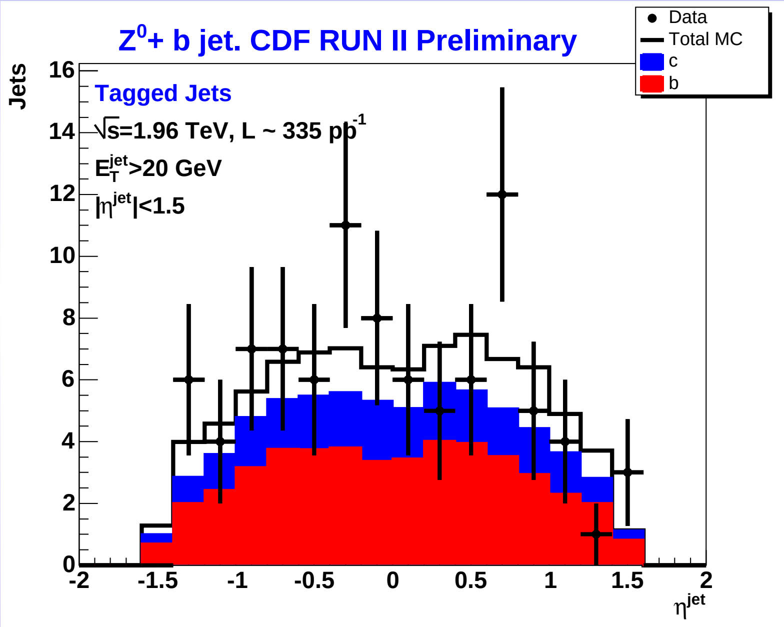

$q\bar{q} \to Z(b\bar{b})$

$Z + 1$ jet (fake rate of 1%)



# CDF result

- Recent study ($335\ \mathrm{pb}^{-1}$), with quite central jets ($\eta < 1.5$).
- The observed events are well described when NLO input is used, for example the pseudorapidity of the tagged jet.




- In the ratio, both theoretical and experimental uncertainties are expected to be reduced. Exptl. errors are already becoming competitive with NLO QCD:

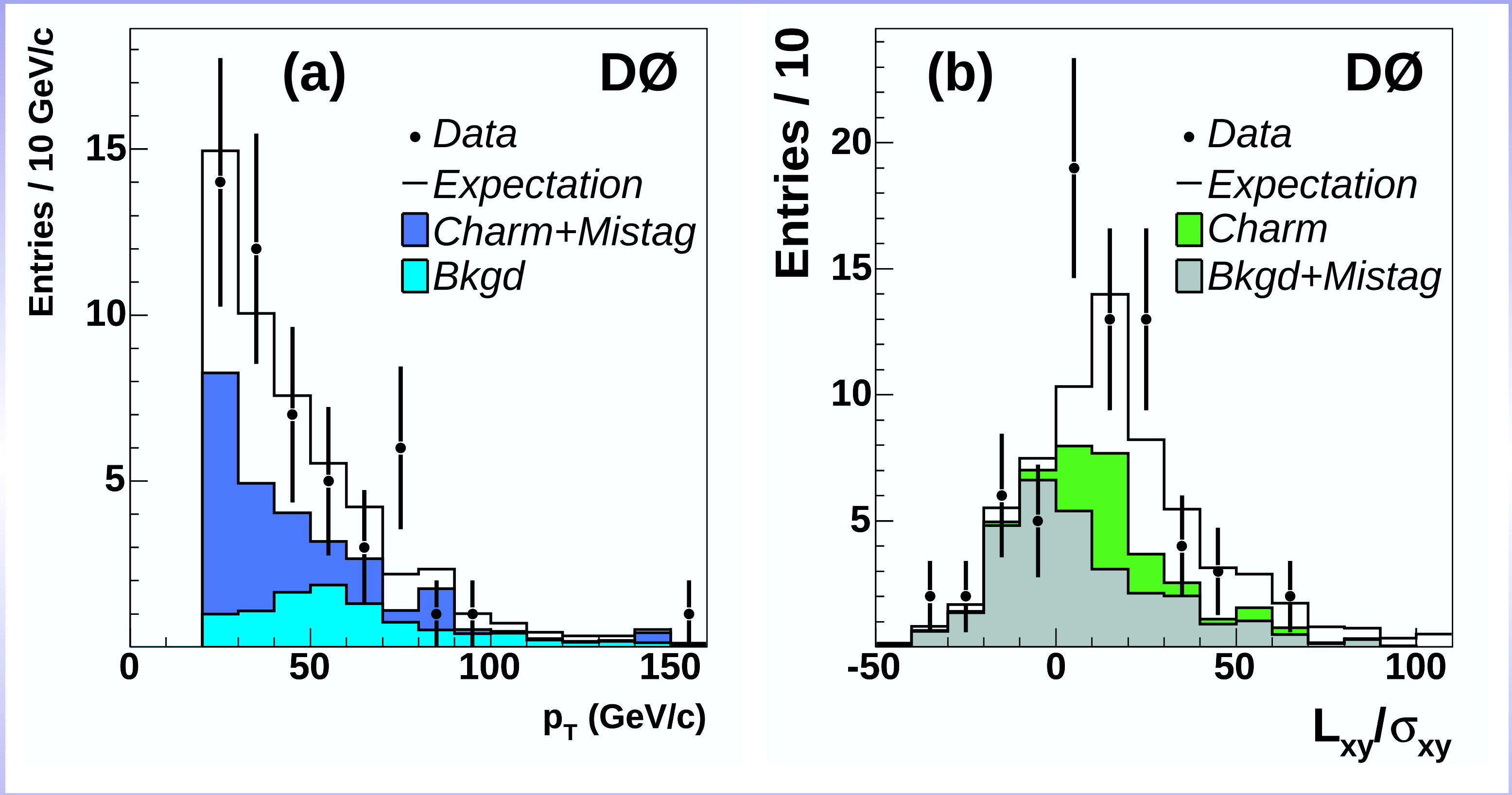
$$\sigma(Z^0 + b\ \text{jet})/\sigma(Z^0 + \text{jet}) =$$

$$0.0237 \pm 0.0078 \pm 0.0033 \quad \text{(CDF Run II)}$$

$$0.0185 \pm 0.0046 \quad \text{(NLO QCD)}$$

- Good agreement so far should give us some confidence.

# D0 result

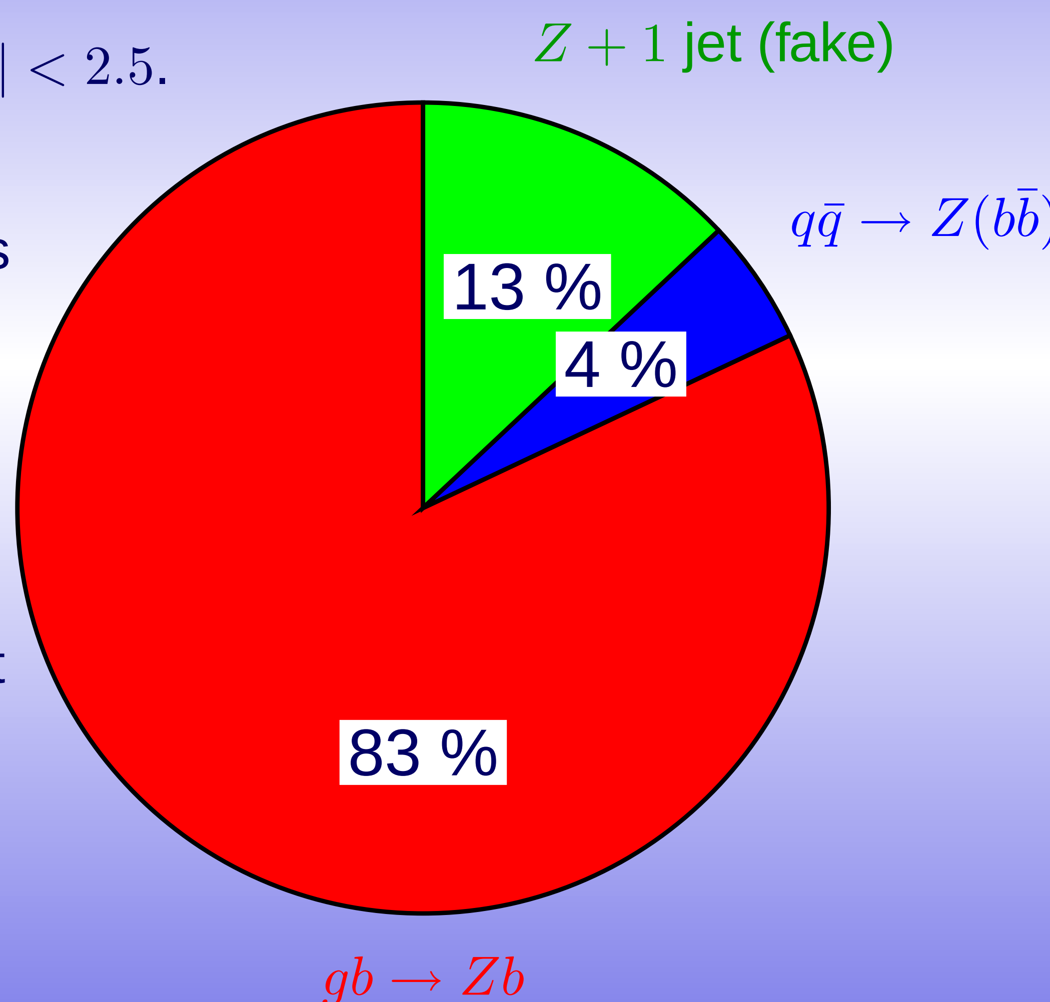



(Dated: February 10, 2005)

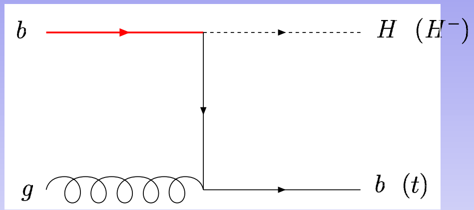
Using the data collected with the DØ detector at $\sqrt{s} = 1.96$ TeV, for integrated luminosities of about 180 pb$^{-1}$, we have measured the ratio of inclusive cross sections for $p\bar{p} \to Z + b$ jet to $p\bar{p} \to Z$+jet production. The inclusive $Z + b$-jet reaction is an important background to searches for the Higgs boson in associated $ZH$ production at the Fermilab Tevatron collider. Our measurement is the first of its kind, and relies on the $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ modes. The combined measurement of the ratio yields $0.021 \pm 0.005$ for hadronic jets with transverse momenta $p_T > 20$ GeV/$c$ and pseudorapidities $|\eta| < 2.5$, consistent with next-to-leading order predictions of the standard model.

# *LHC expectations*

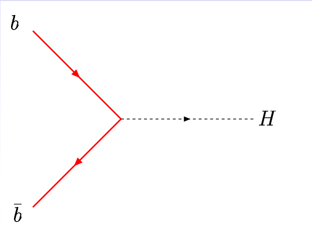
- Cuts: $p_T^{\text{jet}} > 15$ GeV, $|\eta^{\text{jet}}| < 2.5$.
- $\sigma(Z + \text{ one } b \text{ tag}) = 1$ nb.
- Fakes from $Z+$ jet events are much less significant and $q\bar{q}$ contribution is tiny.
- This should allow a fairly clean measurement of heavy quark PDF's (currently, only derived perturbatively).



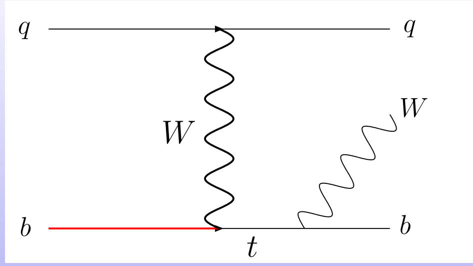
# $b$-PDF uses



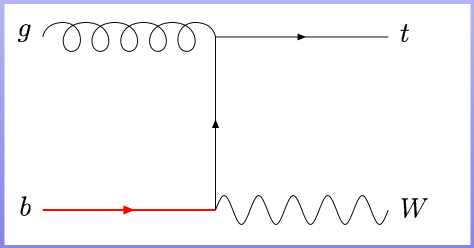

(charged) Higgs+b




inclusive Higgs
(calculated to NNLO,
F. Maltoni et al., hep-ph/0505014)




single-top $qb \to qWb$

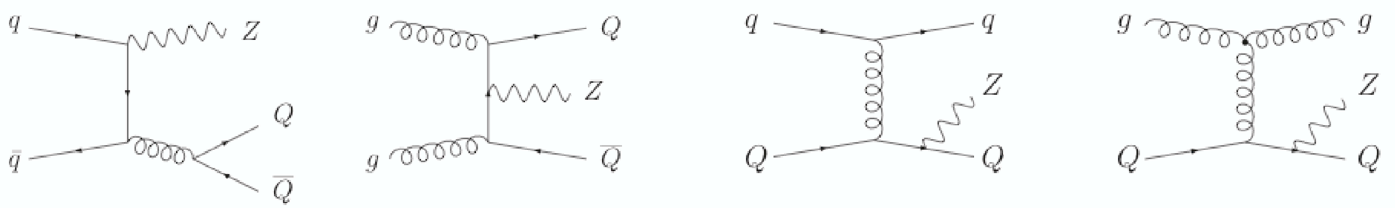



single-top $gb \to tW$

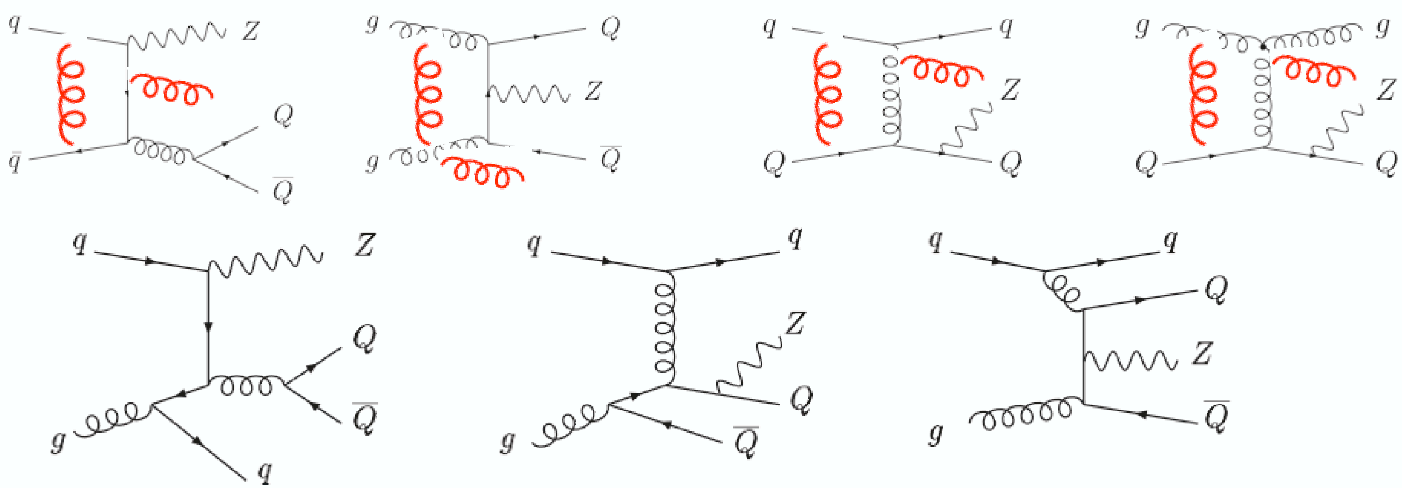
# *The 2-jet sample: $Zb\bar{b}$ and $Zbj$*

What about events which really contain 2 jets, e.g. we consider $Hb\bar{b}$ ?

Leading order:



Next-to-leading order :



For 2 $b$-tags, use $Zb\bar{b}$. If only one $b$ is tagged, what is measured?

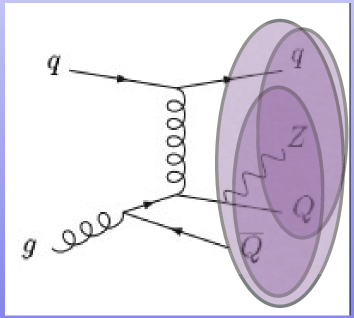
# LHC cross-sections

- Calculations of both processes available at NLO in MCFM.

JC, K. Ellis, F. Maltoni and S. Willenbrock, hep-ph/0510362

| LHC | $\sigma$ (pb) | | | | |
|---|---|---|---|---|---|
| | $ZQj$ | $ZQ\overline{Q}$ | $Z(Q\overline{Q})j$ | $ZQ\overline{Q}j$ | $ZQjj$ |
| bottom | (352) 421 | (109) 92.1 | 23.5 | 60.8 | 92.1 |
| charm | (443) 623 | (87) 75.2 | 58.6 | 49.3 | 123 |
| | $Zjj$ | | | $Zjjj$ | |
| $Z+$jets | (6090) 4840 | | | 1810 | |

- Jets: $p_T > 15$ GeV, $|\eta| < 2.5$.
- $ZQj$ is much larger than $ZQ\bar{Q}$: we should change our picture of $Zjj$ events which contain one $b$-tag.



# *Summary*

- Theoretical predictions for events involving a Higgs or $Z$ boson and a high $p_T$ bottom quark relate to various Higgs searches: $H+b$ (signal), $Z+b$ (test case/background), $Zbj$/$Zb\bar{b}$ (background).
- These calculations can be made in either the 4FS or the 5FS. At sufficiently high order, the approaches should agree.
- For $H+b$ production, this has been tested at NLO – agreement, while not perfect, is adequate.
- For $Z+b$, NLO predictions are available in the 5FS. They agree well with recent data from the Tevatron.
- Events containing a $Z$ boson and $2$ jets, one of which is tagged, are best estimated in the 5FS, with the lowest order process $Zbj$.
- Comparison with data and further study (e.g. matching with parton shower/CKKW/SHERPA) would further improve theoretical understanding.